Technical paper

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Simultaneous Determination of Bimoduli of Asphalt Material with Single Viscoelastic Beam

Xue Li [1] and Linbing Wang [2+]

Abstract: Bimodularity of asphalt material has received attentions from researchers in pavement area since 1960s. The difference of modulus of asphalt mixture in tension and in compression was investigated by applying tension and compression separately to asphalt mixture specimens. This method was time consuming and the experimental deviation for individual tension and compression test can to certain degree confound the different behavior of asphalt material in tension and compression. A new approach was proposed to estimate the modulus in tension and compression simultaneously with a four-point bend beam test on the same asphalt mixture specimen. The value of modulus based on a viscoelastic analysis of the tensile and compressive deformation on the top and bottom of a bend beam was within the range of modulus reported by other literatures. The ratio of the compressive modulus to the tensile modulus increases as temperature increases and/or testing time increases. Furthermore, the observations from this study were reproduced with the data from a previous, completely unrelated test, which confirms the findings from this study.

***Key words**: Asphalt mixture; Beam test; Bimoduli; Rheology; Viscoelasticity.*

Introduction

Asphalt mixture is composed of aggregate particles and asphalt binder. Aggregates form the skeleton of the material and asphalt binder acts as a bonding agent to glue aggregates together. Depending on the aggregate size, the asphalt binder accounts for 7 to 11% of the total volume assuming 4% air voids.

When subjected to external forces, the interlock between aggregates and the bonding force from asphalt binder contribute to the mechanical response of asphalt material and determine the material deformation. However, it seems that the interlock between the aggregates does not provide the same contribution under compressive load and tensile load. This can be observed on non-cohesive sands. Therefore, it is logic to expect the mechanical response of asphalt material is different in compression and in tension.

To further complicate this issue, the material properties of asphalt mixture are loading-rate, temperature dependent. This is mainly due to the viscoelastic nature of asphalt binder in the mixture. In another word, the difference in the mechanical response of asphalt materials in compression and tension could be completely changed as the property of asphalt binder, one of the two main components, varies significantly.

Among many mechanical responses of materials, this research focuses on the modulus of asphalt material, which is one of the most important parameters in designing flexible pavement. In current pavement design methods, the modulus in compression and tension are assumed the same to simplify the analysis of pavement structure. However, two of three major distresses considered in the pavement design, low temperature cracking and fatigue cracking, are mainly referred to mode I fracture, the so called tension fracture, and thus closely related to the mechanical response of asphalt materials in tension. The investigation of the difference of modulus in compression and tension serves as the first step to understand the different behavior of asphalt material in tension and compression and how significant the current design system could be affected by this feature of asphalt mixtures.

Laboratory Testing Program

Bimodularity, i.e. material behavior that materials present two different moduli when subjected to tension and compression, of asphalt mixtures, has received attentions from researchers in pavement engineering long time ago. Secor and Monismith [1] found difference in the strain of asphalt concrete in tension and compression using a creep testing procedure. However, they did not estimate the modulus in tension and compression separately; instead they calculated a combined modulus to describe the mechanical response of asphalt material. Kallas [2] conducted dynamic modulus tests on asphalt mixture specimens subjected to tension, tension-compression, and compression. He found that the measured value of dynamic modulus in tension and tension-compression was around one half of that in compression at 37.8 °C (100 °F) and the difference decreases as the testing temperature decreases. Khanal and Mamlouk [3] conducted all dynamic modulus tests that Kallas has done and static compression and tension tests, and they reached similar conclusions to Kallas's. With different modulus in tension and compression, they found a reduction in the tensile strain at the bottom of AC layer and the vertical compressive strain on the top of the subgrade. Christensen and Bonaquist [4] have reported that the compliance values in tension and compression are not the same even at low temperatures of -20, -10, and 0°C. All above research efforts show that the difference between modulus in tension and compression is lower at lower testing temperature. Daniel and Lachance [5] conducted

[1] Postdoctoral Associate, Virginia Tech, 200 Patton Hall, USA, Tel: (540)231-1568, E-mail xue.li@vt.edu
[2] Associate Professor, Virginia Tech, 200 Patton Hall, USA, Tel: (540)231-5262, E-mail wangl@vt.edu
[+] Corresponding Author: E-mail wangl@vt.edu
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Table 1. Research on the Ratio of Compressive Modulus to Tensile Modulus of Asphalt Mixture.

Authors	Type of Test	Moduli Ratio (Compression to Tension)
Secor & Monisomith [1]	Creep test on a bend beam	N/A(larger difference at higher temperature)
Kallas [2]	Compression, tension, & alternate dynamic modulus test	1.3 at 25°C; 2 at 37 °C
Khanal & Mamlouk [3]	Quasi-static compression & tension by a ramping load; compression, tension & alternate dynamic modulus test	0.86~1.37 at 5°C; 1.10~1.45 at 25°C; 1.50~2.54 at 40°C
Christensen & Bonaquist [4]*	Uniaxial Compression & tension creep test; the IDT test	around 2 at temperatures from -20 to 0°C (larger difference at higher temperature)
Daniel & Lachance [5]	Compression & tension dynamic modulus test	N/A(larger difference at higher frequency)

*: In this research, the compliance was actually measured, instead of modulus.

dynamic modulus tests in tension and compression on asphalt mixtures with 15, 25, and 40% reclaimed asphalt pavement (RAP). They found at 20°C there was no difference between modulus in tension and compression for control mixtures (with no RAP) and mixture with 40% RAP; while the modulus in compression was larger than that in tension for mixture with 15 and 25% RAP. Their data also indicates that when the loading frequency increases, both modulus in tension and compression increase and, however, the difference between modulus in tension and compression increases. This means at the same loading frequency, the difference of modulus in tension and compression increases as temperature decreases, which is a different observation from other research. Note that this was observed on asphalt mixtures with RAP. Table 1 presents a summary of the research reviewed.

In addition, many research efforts [4, 6, 7] have been invested to compare the modulus from compression/tension dynamic modulus to that from indirect tensile test (IDT) [8]. It is well known that the modulus calculated according to the IDT is based on the assumption of the same modulus in tension and compression. Once the bimodularity of asphalt mixture is considered, the IDT modulus is in fact neither compressive modulus nor tensile modulus. More sophisticated analysis is necessary for interpreting the stress and strain distribution and evaluating the modulus in tension and compression in the IDT configuration.

Most of previous research has measured the modulus in tension and compression by applying tensile and compressive load on different sets of asphalt mixture specimens and investigated the bimodularity by comparing the mean values from these sets. Considering the limit of accuracy for dynamic modulus test, listed in Table 2 of AASHTO TP62 [9], and the difficulty in conducting a dynamic modulus in tension, the difference of modulus in tension and compression can be easily concealed by experimental deviations. It is necessary to develop an experiment measuring both moduli from the same specimen and at the same time to minimize experimental effects. This research focuses on determining the moduli in tension and compression from a simply supported asphalt mixture beam and investigating the bimodularity of asphalt mixtures at different temperatures.

Objectives

The objective of this study is to propose a new approach to determine the tensile and compressive moduli of asphalt materials simultaneously using a simply supported beam test. An example at 25 and 40°C is demonstrated and analysis is conducted to evaluate the different behavior of asphalt material in tension and compression as temperature varies.

Materials

Loose mix was sampled out of the daily production at Adams Construction Co., Roanoke, VA. The asphalt binder was produced by Associated Asphalt, Roanoke, VA. The PG grade of asphalt binder was 64-22 and the anti-stripping additive (Adhere HP+) was added into the binder before mixing with aggregates at the amount of 0.5% of the weight of binder. The nominal maximum aggregate size is 9.5mm. The gradation of aggregates is listed in Table 2. The asphalt content is 5.7%. Note that 15% of RAP is used in this mix.

Sample Preparation and Testing

Beam samples were prepared with an AVC vibratory compactor (Pavement Technologies, Inc., Covington, GA). The beam is 381 x 50.4 x 63.5mm (15 x 2 x 2.5inches), in length (*L*), width (*w*), and height (*h*), respectively (Fig. 1). These dimensions are the same as those used for the standard four-point beam fatigue test on asphalt mixtures (AASHTO T321). Loose mixes were compacted in a box-shaped mold at 143°C (290°F) until the designed height is reached. The same amount of asphalt mixes was used to obtain similar density in different beam specimens. During testing, the beam specimen was loaded in the direction perpendicular to the compacting direction in order to minimize the possible density gradient induced by compaction. Note that although specimens with the same dimension have been used to measure the fatigue properties of asphalt mixtures with similar aggregate size, it may not be suitable for asphalt mixes with larger aggregates, which could be due to the consideration on representative volume and/or the fabrication of specimens with uniform quality.

The beam samples were tested at two temperatures: 25 and 40°C with a closed-loop servo hydraulic 100kN load frame (MTS System, Eden Prairie, MN). The beam was bended by two concentrated loads symmetric to the mid span on the top and symmetrically, simply supported at the bottom with a span of 330mm

Table 2. Aggregate Gradation.

Sieve Size, mm	(in)	Percent Passing
12.5	(1/2)	100
9.5	(3/8)	90
4.75	(No. 4)	57
2.36	(No. 8)	38
0.075	(No. 200)	6

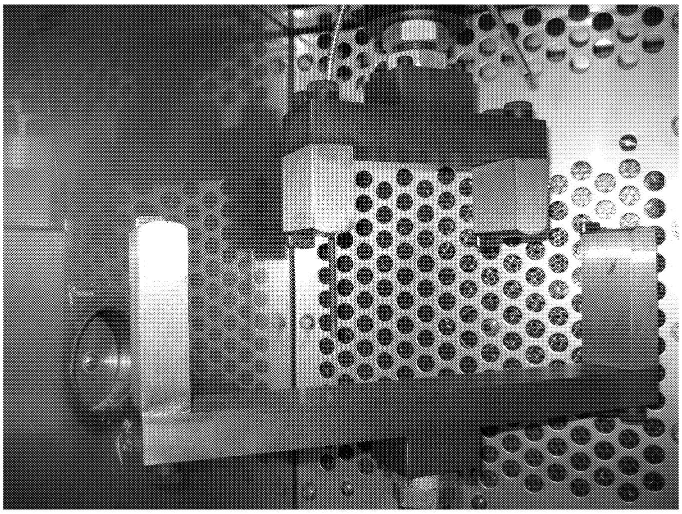


Fig. 1. Testing Setup.

(13inches). This test is similar to the standard third point bend test except the locations of two concentrated loads are not at one third of the span, but 95mm (3.74inches) away from the support. This location of the concentrate load allows enough space to attach the extensometers between loading rollers. During a test, three parameters were recorded at every 0.1 second. The load was measured with a 2kN load cell; the compressive deformation on the top of beam (Δ_c) and the tensile deformation at the bottom of the beam (Δ_t) were measured with strain-gage based extensometers with a gage length of 25mm. Both extensometers were attached at the mid span of the beam. The measurement range of the two extensometers is ±2mm.

A ramping load was applied to the beam at the rate of 5N/s. This loading rate was chosen based on the experiences at 25°C that the target peak load can be reached in reasonable amount of time without introducing significant creep deformation. Depending on the temperature and thus the modulus, the maximum load was varied such that the maximum incurred strain (tensile and compressive strains) was comparable to the previous study [1]. At 25°C, the maximum load was 200N and that corresponded to the data collection time of 40 seconds. The self-weight of the beam was also considered as it may induce measurable strain at relative high temperature.

Beam specimens were kept at the target temperature in an environmental chamber for four hours before testing. This minimized the temperature gradient within the asphalt specimen and consequent modulus gradient, which can invalidate the following analysis of the stress and strain in a beam with bi-modulus.

Elastic Analysis of a Bernoulli-Euler Beam of Bi-Modulus

A simply supported beam is subjected to two equal, concentrated loads symmetric to the center of the span, as shown in Fig. 2. The span of the beam is L and the distance between the support and the location at which a concentrated load is applied is d. The cross section of the beam is shown in Fig. 3(a), with h denoting the height and w the width. The self-weight of the beam is also considered

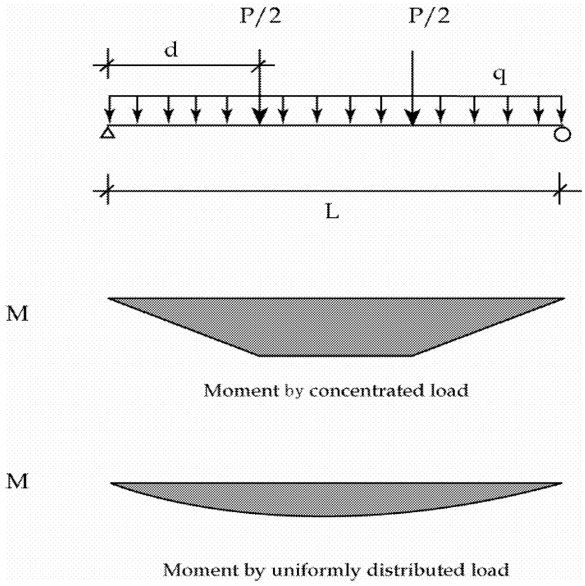


Fig. 2. Loading Configuration.

and denoted as q with unit of N/m, as shown in Fig. 2.

The moments from concentrated loads and uniformly distributed self-weight can be obtained with classical beam theory as described in many structural mechanics books, e.g. Gere and Timoshenko [10]. The moment diagrams from both loads are plotted separately in Fig. 2. The total moment on the beam is obtained using the superposition principle. Let the longitudinal direction of the beam as the direction of X coordinate. For the convenience, the origin of the coordinates is set at the mid span of the beam in the following analysis.

The moment between two concentrated loads is described as

$$M=\frac{Pd}{2}-\frac{q}{2}x^2+\frac{qL^2}{8} \quad \text{for} \quad -\frac{s}{2}\le x\le\frac{s}{2} \tag{1}$$

where s is the distance between two concentrated loads.

The Bernoulli-Euler Beam theory assumes that the transverse plane sections remain plane and normal to the longitudinal fibers after bending. Thus the following relation on strain distribution always exists for a continuous beam.

$$\varepsilon_x=-\kappa y \tag{2}$$

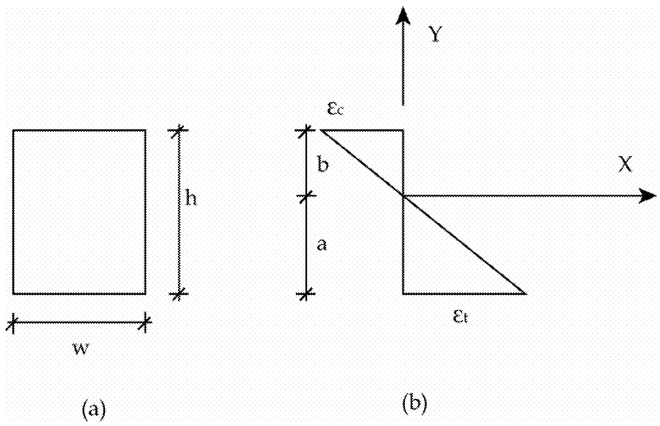


Fig. 3. (a) Beam Cross Section; (b) Strain Distribution.

where κ is the curvature. For a beam with single elastic modulus, i.e. the compressive modulus equals to tensile modulus, the location where strain equals to zero, so-called neutral axis, is at the middle of the height for a cross section shown in Fig. 3(a). When the compressive modulus is different from the tensile modulus, Eq. (2) still holds but the neutral axis does not coincide with the mid-height any more. In Fig. 3(b), the neutral axis is off the middle of the height and distance a away from the bottom fiber and b from the top fiber. The strain corresponding to distance a is the largest tensile strain and denoted as ε_t. Similarly, ε_c is used to denote the largest compressive strain at distance b. With the geometry in Fig. 3, it is obtained that

$$\frac{\varepsilon_t}{\varepsilon_c}=\frac{a}{b}=r \tag{3}$$

Based on the balance of force at the cross section, i.e. $\sum F=0$, it can be written as

$$\int_{-a}^{0}\sigma_t^{'}dA+\int_{0}^{b}\sigma_c^{'}dA=0 \tag{4}$$

where $\sigma_t^{'}$ and $\sigma_c^{'}$ are tensile and compressive stresses distributed along the height respectively. Solving Eq. (4), it is obtained that

$$\frac{E_t}{E_c}=\frac{b^2}{a^2}=\frac{1}{r^2} \tag{5}$$

Let us consider the resultant moment from the stress acting over the cross section.

$$M=\int_{-a}^{0}\sigma_t^{'}\,y\,dA+\int_{0}^{b}\sigma_c^{'}\,y\,dA \tag{6}$$

With some simple integration

$$M=\frac{w}{3}(E_t\cdot a^2\cdot\varepsilon_t+E_c\cdot b^2\cdot\varepsilon_c) \tag{7}$$

where E_t and E_c are tensile and compressive moduli, respectively. With Eq. (5), Eq. (7) can be reduced to

$$M=\frac{w}{3}E_c b^2(1+\frac{a}{b})\varepsilon_c \quad =\frac{w}{3}E_t a^2(1+\frac{b}{a})\varepsilon_t \tag{8}$$

In this study, two extensometers are used to measure the deformation of the outside fiber of the beam. One extensometer is attached on the top and the other at the bottom of the beam and along the longitudinal fiber. The center of extensometer is aligned with the mid span of the beam. Next, the deformation of gages mounted on the beam is estimated. With self-weight, the pure bending does not exist in between the two concentrated loads. The deformation measured by the extensometers should be calculated by

$$\Delta_t=\int_{GL}\varepsilon_t dx \tag{9a}$$

$$\Delta_c=\int_{GL}\varepsilon_c dx \tag{9b}$$

where GL is the gage length. With relationship in Eq. (3), Eq. (9a) can be expressed as

$$\Delta_t=\int_{GL}\frac{a}{b}\varepsilon_c dx=\frac{a}{b}\Delta_c \tag{9c}$$

Thus we have

$$\frac{\Delta_t}{\Delta_c}=\frac{\varepsilon_t}{\varepsilon_c}=\frac{a}{b}=r \tag{10}$$

With Eqs. (8) and (9), it can be derived after applying some calculus that

$$E_c=\frac{A_1P+A_2q}{\Delta_c} \tag{11}$$

where $A_1=\dfrac{3d\cdot GL}{2wh^2}(1+r)$

$$A_2=\frac{GL}{8wh^2}[3L^2-(GL)^2)](1+r)$$

and P is the applied concentrated load and Δ_c the compressive deformation measured by the extensometer attached on the top of the beam. When Eq. (5) is applied, the tensile modulus, E_t, can also be easily derived.

Viscoelastic Analysis of a Beam of Bi-Modulus

The correspondence principle was used to develop the solution considering asphalt mixture as a viscoelastic material. This principle states that the solution to the problem for a viscoelstic continuum is closely related to the solution to a corresponding problem for an elastic continuum occupying the same geometric configuration and subjected to the same boundary conditions. The only difference between these two solutions is that the elastic constants and items in the elastic problem are replaced by their appropriate transforms in the viscoelastic problem. In this study the Laplace transformation was used.

The viscoelastic solution was obtained through the following steps:

1. Conduct the Laplace transformation of two loading functions and one deformation function.
2. Replace items with their corresponding Laplace transforms in Eq. (11). That is
   $E(t)\rightarrow s\bar{E}(s)$, $P(t)\rightarrow\bar{P}(s)$, $\Delta(t)\rightarrow\bar{\Delta}(s)$
3. Solve the equation in the Laplace domain.
4. Invert the solution in the Laplace domain back into the time domain.

The loading functions in the time domain are

$$P(t)=p_0\cdot t \quad ; \; q(t)=q_0\cdot U(t) \tag{12}$$

where $U(t)$ is a unit step function; p_0 and q_0 are the magnitudes of the load. The form of the deformation function, $\Delta(t)$, was obtained by the regression on the experimental data.

Analysis of Data

Experiment at 25°C (77°F)

Six beams were tested at 25 °C. The measured tensile deformation at the bottom of the beam was plotted against the compressive deformation on the top of the beam in Fig. 4. Note the

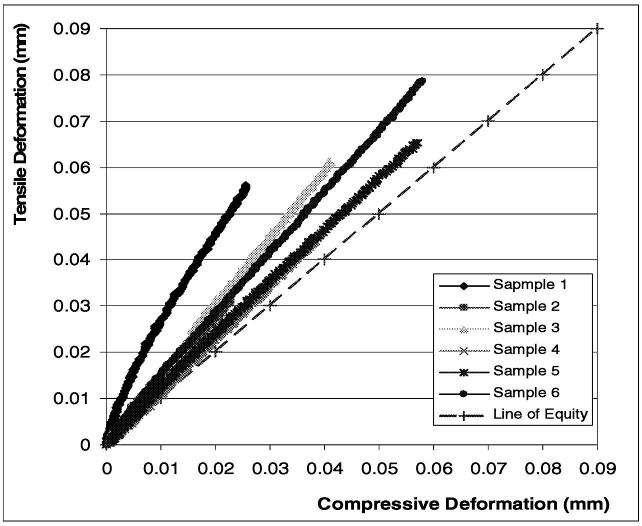


Fig. 4. Deformations at 25°C.

deformations plotted were the extension or compression measured by extensometers and they are Δ_t or Δ_c in Eq. (9) and they are not the corresponding strains, which varies within the gage length. As expected, the compressive and tensile deformation changed proportionally and a linear regression typically resulted in good fit.

The slope of the regression curve evaluated the ratio *r* used in above derivation. The values of the slopes listed in Table 3 average at 1.28 with a standard deviation of 0.14. With Eq. (5), this indicates the compressive modulus, E_c, is around 1.6 times larger than the tensile modulus, E_t. This value agrees with the observations by previous research listed in Table 1.

The compressive deformation curve was used to obtain the deformation function, $\Delta(t)$ in Eq. (11). The typical compressive deformation was plotted in Fig. 5. The best fit was a second order polynomial as

$$\Delta(t)=2\times10^{-5}t^2+4\times10^{-4}t \tag{13}$$

Laplace transformation was performed on Eqs. (12) and (13) and transformed functions were plugged in the following equation

$$\overline{E}(s)=\frac{A_1\overline{P}(s)+A_2\overline{q}(s)}{s\overline{\Delta}(s)} \tag{14}$$

The inverse Laplace transformation was then applied to obtaining the relaxation modulus function in the time domain as

$$E(t)=1.524\times10^{10}e^{-0.1t}-1.574\times10^{11}\delta(t) \tag{15}$$

where $\delta(t)$ is the Dirac Delta function and this item in Eq. (15) is related to the initial material response. The relaxation modulus was plotted in Fig. 6 and the values at certain time points were calculated and listed in the same figure. These values of relaxation modulus are comparable with the values reported in the literatures

Table 3. The *r* Ratio at 25°C.

Beam 1	Beam 2	Beam 3	Beam 4	Beam 5	Beam 6	Mean	Standard Deviation
1.97*	1.27	1.48	1.16	1.14	1.34	1.28	0.14

*: This is an outlier and not included in the calculation.

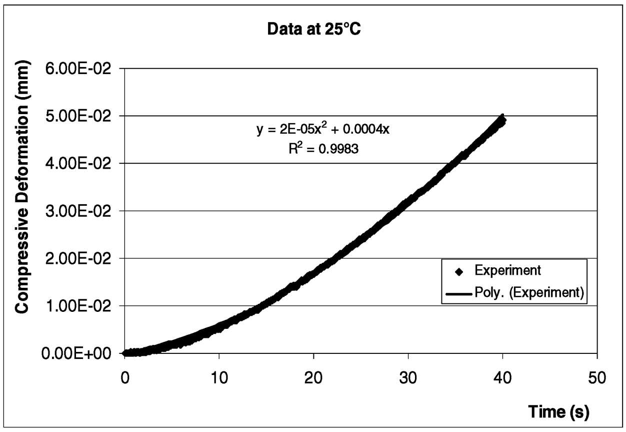


Fig. 5. Compressive Deformation at 25°C.

[1, 3]. The modulus evaluated with only the elastic solution in Eq. (11) was plotted in the same graph. The obvious difference between these two curves implies the necessity of a viscoelastic solution.

Analysis of Data at 40°C (104°F)

It was attempted to test these beams at 40°C. The tests at 40°C were planned on the next day after the finishing of tests at 25°C to provide enough rest time for beams to recover from any creep incurred during the test.

The creep induced by the self-weight at 40°C was so significant that large deformation were introduced even without applying the concentrated load. A typical set of measured compressive and tensile deformation was plotted in Fig. 7. Note that the deformation at the end of the test approximately corresponded to 12,000$\mu\varepsilon$. However, the test procedure used at 25°C could not capture the initial response of asphalt material, as between the time setting up the beam on the fixture and the time starting the data acquisition system the creep data were not recorded by the system. This means in the response of asphalt material, as between the time setting up the beam on the fixture and the time starting the data acquisition system the creep data were not recorded by the system. This means in the above viscoelastic analysis a function with non-zero values at times before t=0 needs to be used and this will significantly

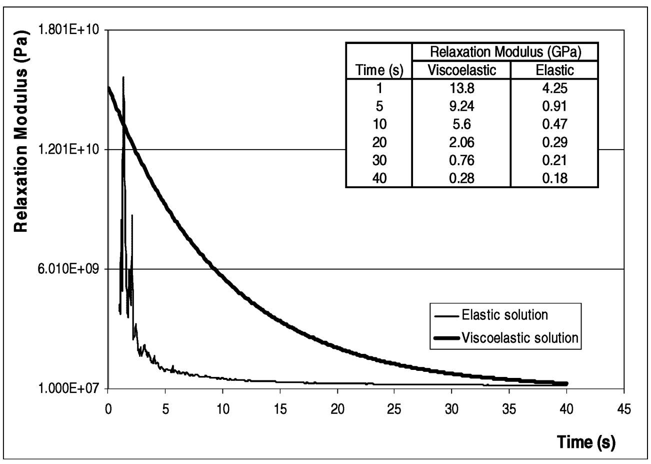
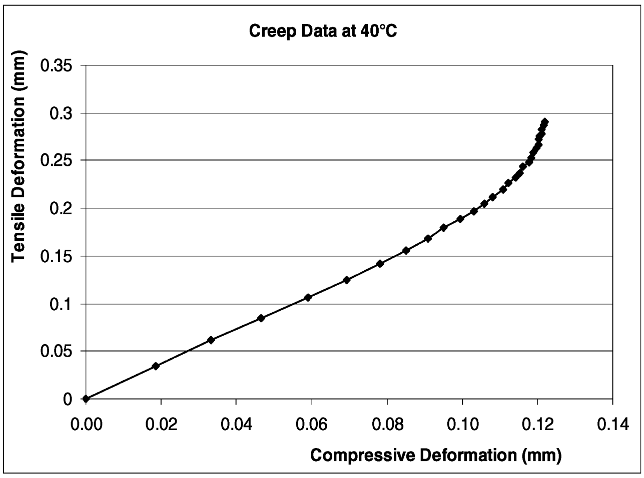


Fig. 6. Modulus Estimated by Elastic and Viscoelastic Solutions.



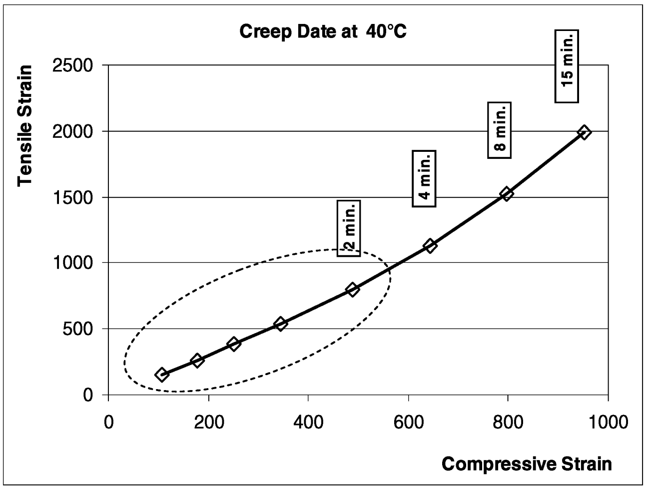
Note: The time *t*= 0 was not the beginning of creep, but the starting of data recording.

Fig. 7. Strains at 40˚C.

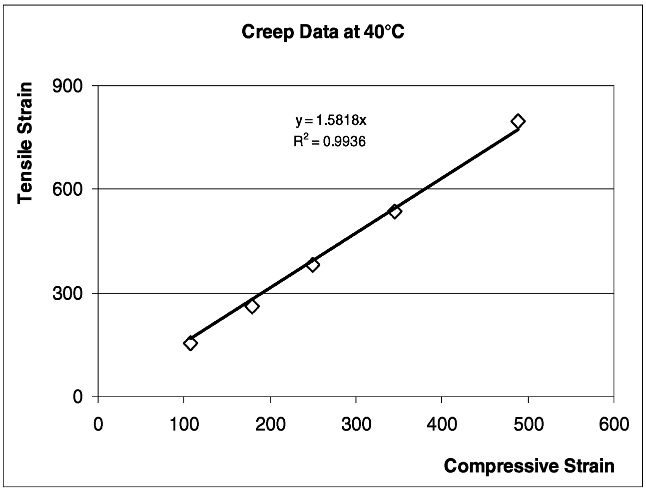
Table 4. Tensile and Compressive Strains by Secor and Monismith [1].

Time (Minute)	Compressive Strain (μ in. per in.)	Tensile Strain (μ in. per in.)
*	107	155
*	179	262
*	250	381
*	345	536
2	488	798
4	642	1131
8	798	1524
15	952	1988

*: The corresponding time cannot be determined from the figure.



(a)



(b)

Fig. 8. Compressive and Tensile Strains by Secor and Monismith [1].

increase the complexity of the analysis. It was reasonable to revise the experimental procedure rather than redeveloping the viscoelastic analysis. Therefore, data at 40˚C was not subjected to the same analysis as that at 25˚C. Therefore, data from a revised version of the proposed experiment in this work will be analyzed in the future work.

However, it was worth investigating the general trend of the change of compressive and tensile deformation measured from the same material, but different fashions of loading, e.g. creep at 40˚C versus constant rate of stress at 25˚C.

At the left side of Fig. 7, the compressive and tensile deformations increase proportionally and the curve is close to a straight line, like that at 25˚C in Fig. 4. As both deformations increase further, the tensile deformation seems change faster than the compressive deformation and the curve becomes non-linear and bends up, which indicates an increasing slope, i.e. *r* ratio. This seems imply the above analysis become invalid at large deformation and/or long test time.

Discussion

It is interesting to find that a similar bend test on an asphalt mixture beam was performed by Secor and Monismith [1]. They reported the tensile and compressive strains measured at the same time subjected to a creep load. These strains can be used to test the approach proposed in the current paper.

In their beam test, the beam specimen was set vertically and a system of pulleys and weights was used to create a pure bend along the beam and apply the constant bending moment instantaneously. They measured the compressive and tensile deformations, but they derived a combined modulus other than tensile and compressive modulus separately. Their data in this creep test at 25˚C (77˚F) were extracted from Fig. 5(b) in paper [1] and listed in Table 4. Unlike the original paper, the compressive and tensile strains were plotted against each other in Fig. 8(a). This curve is similar to the curve obtained at 40˚C rather than that at 25˚C in this study. Note that Secor and Monismith collected their data up to 15 minutes and only 40-second data were collected at 25˚C in this study. A closer look of Secor and Monismith's data at time less than 2 minutes was presented in Fig. 8(b). This part of data appeared to be fairly linear and a linear regression gives a slope, i.e. *r* ratio in this study, of 1.58 and an *R*-value of 0.9936. This *r* ratio is different but close to the *r* ratio (1.28) obtained from this study. Considering the two tests were conducted by two different groups with two different types of loads on two different asphalt mixes, the difference in the *r* ratio is not that significant. Apparently, the observations of a constant ratio between the tensile and compressive modulus at short testing time in this study can be reproduced from Secor and Monismith's study in 60s.

Furthermore, Fig. 8 based on Secor and Monismith's study seems include both features of tensile-compressive deformation curves at 25 and 40°C: constant r ratio and linear variation at short time and/or low temperature, and increasing r ratio and non-linear variation at long time and/or high temperature. This can be partly explained by two aspects of asphalt materials. First, the difference of interlock at different stress states; At the compression side of the beam, when the compressive stress increase to certain level, the material becomes difficult to be compressed due to the interaction of aggregates; at the tension side of the beam, when the tensile stress reaches certain level, the effect of interlocking degrades significantly, the air void opens and the microcrack nucleates. This large deformation may invalidate the plane assumption in the beam theory, i.e. the transverse section planes become curve planes. Then the relationship between the compressive and tensile strain described in Fig. 3 and Eq. (3) does not hold any more and the above analysis cannot be applied to derive the relaxation modulus from the beam test. Second, the time-temperature superposition of thermorheologically simple material; as reported by most of the studies listed in Table 1, the higher the testing temperature, the larger the difference between the tensile properties and the compressive properties. In the context of the approach employed in this study, this observation indicates that the r ratio increases as the temperature increases. With the time-temperature superposition, the material response at longer time and reference temperature is equivalent to that at short time and higher temperature. This means at the same temperature the r ratio should be larger at longer time than at shorter time and this explains the bending-up of the tensile-compressive deformation curve.

Conclusions

A four-point bend beam test was fabricated to measure the tensile modulus and compressive modulus simultaneously by innovatively interpreting the tensile and compressive deformation data measured with two separate strain gages. Viscoelastic analysis was employed to evaluate the relaxation modulus of asphalt materials in tension and compression, and to investigate the change of the mechanical response of asphalt materials in tension and compression at different temperatures. Based on the limit experimental data, it is observed that

1. The relaxation modulus evaluated by the approach developed in this study is comparable to the values of modulus by various techniques reported in literatures. And it is shown that at 25°C the viscoelastic solution is different from the elastic solution.
2. The ratio of compressive modulus to tensile modulus changes when temperature and loading frequency change. The higher the temperature and/or the lower the loading frequency, the larger the ratio and the more significant the difference of mechanical response of asphalt material in tension and compression.
3. The observation in this study has been reproduced by using experimental data from a completely different study on a different load and a different type of asphalt material.

It should be emphasized that the goal of this study is to demonstrate a new method to investigate the bimodularity of asphalt mixtures. More asphalt mixtures are to be tested to evaluate the limit of accuracy of the relaxation modulus derived from this approach and the relationship of this modulus to other types of modulus that measured according to the current standard tests, and more temperatures are to be tested to confirm the observation on the change of the ratio of compressive modulus to tensile modulus.

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Disclaimer

Neither of the sponsoring agencies necessarily concurs with, endorse, nor adopt the findings, conclusions or recommendations either inferred or expressly stated in subject data developed in this study.

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